$\begin{array}{c} {\bf Electroacoustic~Evaluations~of~1-3}\\ {\bf Piezocomposite~SonoPanel^{TM}~Materials} \end{array}$

Thomas R. Howarth, Member, IEEE, and Robert Y. Ting

Abstract—An advanced configuration 1-3 piezocomposite, designated by its manufacturer as $SonoPanel^{TM}$, has been investigated for potential underwater acoustical applications. In-air electromechanical characteristics and inwater acoustical properties of the $SonoPanel^{TM}$ were experimentally examined. The in-air impedance measurement results showed the existence of parasitic modes in the composite panel in addition to the expected thickness mode. This modal behavior is identified to be related to the piezocomposite structure. In-water acoustical properties of the new 1-3 piezocomposite panels were investigated as a function of temperature, hydrostatic pressure, and frequency. The effect of underwater explosive shock on the acoustic responses showed no detrimental effects in mechanical structure or acoustical performance of the piezocomposite panel. Linearity with electrical drive level and hydrostatic pressure stability of the 1-3 piezocomposites also were established. These results suggest that the SonoPanelTM piezocomposite material is potentially useful for underwater acoustical applications, particularly in applications in which large area coverage is desired.

I. Introduction

 $\mathbf{P}_{\text{IEZOELECTRIC}}$ ceramics such as lead-zirconate-titanate (PZT) compositions have been used in underwater transducer applications for many years. These bulk ceramics are dense, heavy and of limited size and shape so that they are rather difficult to apply for large area coverage. For applications involving the coverage of a large surface, the transducers function in a hydrostatic mode, which means they are needed to be operational over an extended frequency band as opposed to a purely resonant device that operates in a pure "33" mode. The piezoelectric voltage coefficient in this mode (g_h) is related to the longitudinal and transverse direction coefficients through the following relationship:

$$g_h = g_{33} + g_{32} + g_{31}. (1)$$

Unfortunately, in PZT ceramics both the coefficients g_{31} and g_{32} have magnitudes nearly equal to half that of g_{33} but are of a different sign [1]. This results in a very small g_h , or a very poor hydrostatic mode response [2]. Therefore, new materials with improved hydrostatic piezoelec-

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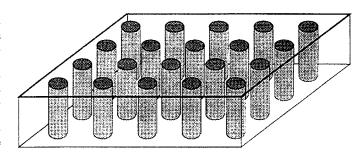


Fig. 1. Schematic representation of a 1-3 piezocomposite material structure.

tric properties that are also light, flexible, and/or conformal are being sought. In addition, it is highly desirable that the new materials be processed at low cost to form large sheets for applications that demand the coverage of large area surfaces.

Research work pioneered at the Pennsylvania State University's Materials Research Laboratory has led to the development of a large variety of piezoelectric composite materials that consist of a ceramic and a polymeric phase with different connectivities [3]. The self-connectivity in one, two, or three dimensions in a composite is designated as "1, 2, or 3". Therefore, a piezocomposite consisting of thin piezoelectric ceramic rods aligned in parallel and embedded in a polymeric resin matrix is called a "1-3" composite. The ceramic rods are connected in only one direction, the poled direction of the material, with a connectivity of "1". However, the polymer phase is connected in all three dimensions, with a connectivity of "3". Fig. 1 shows a schematic of the 1-3 piezocomposite concept. In recent years this type of piezoelectric composite material has been investigated for applications in large-area hydrophones and as high-frequency underwater imaging transducers [4], [5].

In this paper, the results of an investigation on a specific 1-3 piezocomposite material configuration is reported and discussed. The configuration is a trademarked product named the SonoPanelTMas developed and manufactured by Material Systems, Inc. (MSI), Littleton, MA [6]. The in-air characteristics of these materials, as well as their in-water acoustical properties, have been measured. The effects of temperature, hydrostatic pressure, and underwater explosive shock on the acoustic performance of the materials as an underwater transducer were examined.

II. SONOPANELTMCONFIGURATION

Conventional 1-3 piezocomposite materials typically have been fabricated by using a dice-and-fill method,

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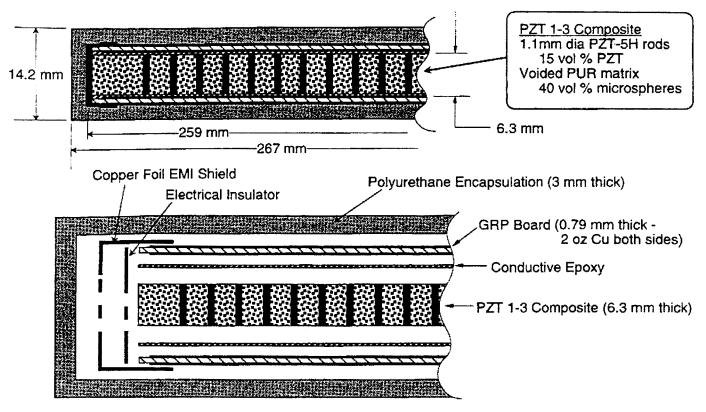


Fig. 2. Cross-sectional view of the SonoPanelTM 1-3 piezocomposite structure [6].

which is adequate for the preparation of small samples such as required in ultrasonic medical imaging applications [5]. However, this method is too costly to meet the need of large area coverage desired in Navy applications, and it is difficult for maintaining material uniformity in large sheets. To meet the Navy application interests, the Office of Naval Research has supported a number of initiatives to explore alternative, low-cost fabrication techniques for the manufacturing of large sheets of 1-3 piezocomposite materials.

One approach is that of MSI in which an injection molding process [6] is used to manufacture 1-3 piezoceramic composites. The initial piezoceramic of choice was Navy Type VI (PZT-5H) piezoceramic powder composition, although MSI has since produced configurations with Navy Type I (PZT-4). Once properly characterized, the piezoceramic powder is thoroughly mixed with a binder to form a viscous slurry. During the injection molding process, the slurry mixture is forced into a cooled mold to form a net shape green part. This part is subsequently heated in air for the removal of the organic binder. Sintering then takes place at 1250°C for one hour in a lead controlled atmosphere to optimize the PZT piezoelectric properties. The preform is then contact poled under a high electric field. Individual preform parts are assembled to the size of a desirable transducer panel and encapsulated by using castable resins such as polyurethane or epoxy under applied pressure. The panel assembly is subsequently cured in a vacuum oven, cooled, and finished before permanent electrodes are applied and wires attached. The final base configuration is a $50 \times 50 \text{ mm}^2$ preform, containing a 19×19 array of 361 rods. Each rod is 1.1 mm in diameter and about 6.5 mm in height.

Because the original Navy need was for large area hydrophones, MSI initially fabricated the material to address this application. Using published analytical design principles in which the g_h was found to be maximized at the 15% piezoceramic volume fraction [7] with rod aspect ratios on the order of 5 [4], MSI concentrated their early efforts with these material design parameters. The hydrophone intention also implied that the preferred host matrix material should be a soft and lossy polyurethane with a stiff cover plate. The soft and lossy matrix was ensured by placing a 40% volume of 50- μ m diameter hollow polymer microspheres into the polyurethane, thus reducing the lateral coupling within the composite structure. Fig. 2 shows a schematic side drawing of the SonoPanelTM1-3 piezocomposite material configuration.

The purpose of the cover plates is to average out and stress amplify the incident sound pressure upon the individual piezoceramic rods as well as to provide an electrically solderable connection point. The cover plates are attached by bonding 0.79-mm thick copper clad glass reinforced polymer board (GRP) with a 0.08-mm thick layer of conductive epoxy.

With the interest in hydrophone applications, there also was a concern that the electromagnetic interference (EMI) between neighboring sensors had the potential of being a noise floor problem and thus limiting the signal-to-noise ratio of the hydrophone. To address this, the individual

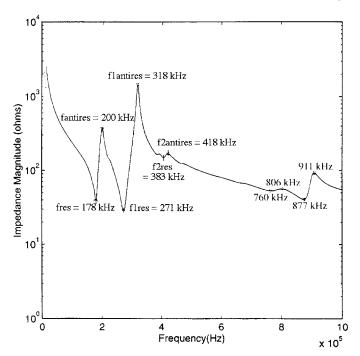


Fig. 3. In-air impedance magnitude of a SonoPanelTM with dimensions 10.16 cm by 10.16 cm by 6.35 mm.

panels were shielded by placing a copper foil tape over the edges with an insulating layer placed inside the foil. The shielding foil is soldered to the outer copper sheets along the interfacing edge to form a completely grounded enclosure for the panels.

A 15% piezoceramic volume fraction, Navy Type VI piezoceramic rods based 1-3 piezocomposite SonoPanelTM, has a nominal dielectric constant of 3200 and a density of 1.8 g/cm^3 in which the dielectric constant is simply the volume percentage of the piezoceramic component.

III. IN-AIR EVALUATIONS

A candidate 15% piezoceramic volume fraction, PZT-5H sample was evaluated in-air for its effective material properties. The sample was 10.16 cm by 10.16 cm by 6.35 mm thick with a spacing of 2.58 mm between each of the cylindrical rods in both the -1 and -2 directions. The measured 1 kHz free capacitance was 8.84 nF with a 0.023 dissipation factor (tan δ), from which was derived an effective composite free relative dielectric constant (K_{33}^T) of 614.

A measurement of the normal displacement of the radiating surface using laser Doppler vibrometry (LDV) was done at the Naval Research Laboratory in Washington, DC, as a function of frequency for a 1 V drive. This measurement was used to determine an effective longitudinal piezoelectric charge constant (d_{33}) of 562 pm/V, which is within expectations of current Navy Type VI (PZT-5H) material properties.

The effective longitudinal and shear velocities were determined at the former Naval Research Laboratory's Underwater Sound Reference Detachment (USRD) in Or-



FREE-FIELD VOLTAGE SENSITIVITY

Prezocomposite Transducer
Open-direuit voltage measured at end of 15.0-m cable; Unbalanced
Water Temp: 30° C
Depth: 3.9 m (38 kPa)
8.9 nF Capacitance measured of end of 15.0-m cable

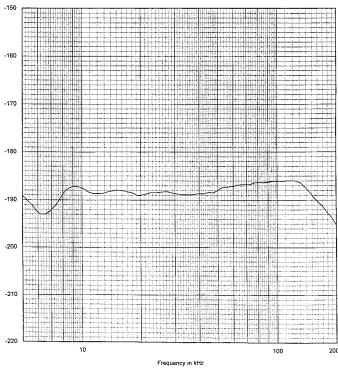


Fig. 4. Measured FFVS of a 10.16 cm by 10.16 cm by 6.35 mm Sono Panel $^{\rm TM}$ in an open water Lake Facility.

lando, FL. An effective longitudinal velocity of 2260 m/s was determined by placing transducers on both surfaces of the SonoPanelTM sample and measuring the time of flight between the transducers. The shear velocity of the voided polyurethane matrix material (ν_p^s) was determined on a representative matrix material sample as 700 m/s.

Fig. 3 shows the impedance measurement over the frequency range of 100 Hz to 1 MHz. In addition to the expected thickness mode resonance at 178 kHz and the antiresonance frequency at 200 kHz, several other modes are present. Investigations of these modes has found that they generally are related to lateral behavior through the following:

$$f_1 = \nu_s^p / d \tag{2}$$

and

$$f_2 = \sqrt{2} * \nu_s^p / d \tag{3}$$

where d is the spacing between piezoceramic rods, f_1 is the first lateral mode in which the piezoceramic rods and the host matrix vibrate in anti-phase along any diagonal and in-phase along the -1 and -2 directions, and f_2 is the second lateral mode in which the piezoceramic rods and the host

LAKE FACILITY

FLORIDA 32856-8337

TRANSMITTING VOLTAGE RESPONSE

Piezocomposite Transducer
Pressure at one meter per volt applied at end of 15.0-m cable; Unbalanced
Water Temp: 30° C
Water Temp: 30° C
Water Sept. 30° C

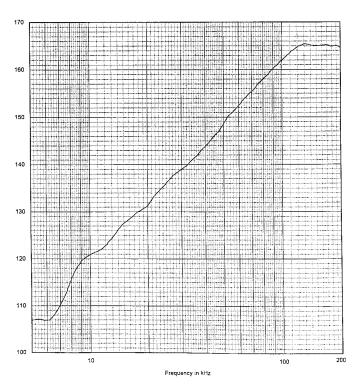


Fig. 5. Measured TVR of a 10.16 cm by 10.16 cm by 6.35 mm Sono Panel $^{\rm TM}$ in an open water Lake Facility.

matrix vibrate in-phase along any diagonal and in antiphase along the -1 and -2 directions (D. Powell, personal communication and unpublished model, April 9, 1996). However, note that these expressions are approximations and do not account for the influence of the cover plates but provide a general guideline of the expected modal behavior.

The upper frequency modal behavior is related to the dimensional geometry and material constituents of the individual piezoceramic rod in which Fig. 3 shows the radial resonance frequency at 877 kHz and the antiresonance frequency at 911 kHz.

IV. OPEN WATER ACOUSTIC PERFORMANCE MEASUREMENTS

Underwater free-field acoustical performance measurements of the 1-3 piezocomposite SonoPanel $^{\rm TM}$ material configurations were performed at the USRD Lake Gem Mary Facility in Orlando, FL. These measurements consisted of free-field voltage sensitivity (FFVS), transmitting voltage response (TVR), acoustic directivity responses, and power linearity as a function of drive voltage. The frequency coverage of the measurements was from 100 Hz to 200 kHz.

UNDERWATER SOUND REFERENCE DETACHMENT P. O. BOX 568337, ORLANDO, FLORIDA 32856-8337

LAKE FACILITY

DIRECTIONAL RESPONSE

Depth: 3.9 m (38 kPa) Water Temp: 30° C Receive, XY Plane, 10 kHz

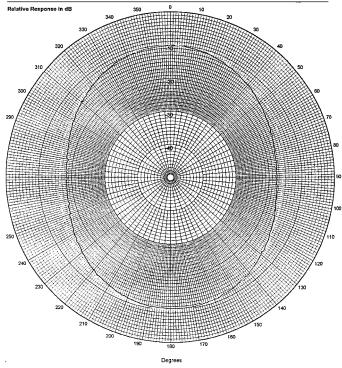


Fig. 6. Measured 10 kHz directivity response of a 10.16 cm by 10.16 cm by 6.35 mm SonoPanel $^{\rm TM}$ in an open water Lake Facility.

The first SonoPanelTM geometry investigated was an active 10.16-cm by 10.16-cm by 6.35-mm sample that was encapsulated in polyurethane for water protection. Fig. 4 shows the free-field voltage sensitivity in units of decibels (dB) referenced to 1 V per micropascal at the face of the sample. The response was not corrected for the electrical load due to the cable capacitance which means that the sensitivity response should be increased by an additional decibel. A low frequency mode below 10 kHz is believed to be related to flexure within the cover plates. The remainder of the response is fairly constant throughout the frequency band until 130 kHz, when the response begins to roll off. This lower frequency resonance frequency roll off (as compared to the observed in-air thickness resonance frequency of 178 kHz) may be partially attributed to the additional mass loading onto the sample from the polyurethane encapsulant.

The transmitting voltage response (TVR) of the SonoPanelTM sample is shown in Fig. 5. The TVR is reported in decibels referenced to one micropascal per volt at 1 meter. In addition to the thickness mode near 130 kHz, both plots also show the presence of additional modes between 130 kHz and 200 kHz, the origins of which are believed to be related to the spacing between the piezoceramic rods. The increase in TVR with frequency is slightly



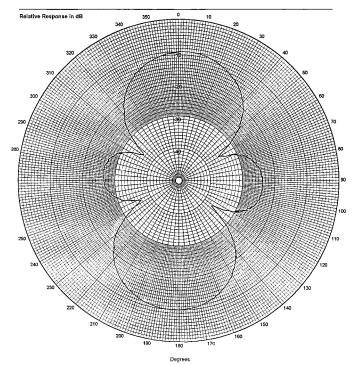


Fig. 7. Measured 20 kHz directivity response of a 10.16 cm by 10.16 cm by 6.35 mm SonoPanel $^{\rm TM}$ in an open water Lake Facility.

greater than the normal 12 dB per octave change, indicative of the overall panel displacement being different from that expected of an idealized point source. The main reason for this difference is the presence of the parasitic modes observed in-air; however, the behavior between 130 and 200 kHz appears to result in a response with improved acoustic bandwidth. An attractive feature of the TVR is the general lack of other modes in the frequency range of 10 to 130 kHz that would normally be noted in a transmit response due to the dimensional features of a transmitting panel.

Fig. 6 and 7 show the acoustic directivity responses of the same sample at 10 and 20 kHz, respectively. The responses are well behaved and indicative of a pure piston mode transduction mechanism of the same dimensions.

A 25.4-cm by 25.4-cm by 6.35-mm thick SonoPanelTM geometry was similarly water protected with a polyurethane encapsulation, then investigated for its acoustic performance in the Lake Gem Mary Facility. Fig. 8 shows the FFVS for this sample. It appears in good agreement with the response of the smaller sample response shown in Fig. 4, including similar modal behaviors and sensitivity levels with the exception of the thickness resonance frequency observed to occur at 100 kHz; this is down from the 130 kHz observed in Fig. 4. The TVR of this sample is presented in Fig. 9, and the same modal behavior

UNDERWATER SOUND REFERENCE DETACHMENT

LAKE FACILITY

FREE-FIELD VOLTAGE SENSITIVITY

Piezocomposite Transducer
Open-circuit voltage measured at end of 15.0 -m cable
Water Temp: 30° C
Depth: 3.9 (38 kPa.)

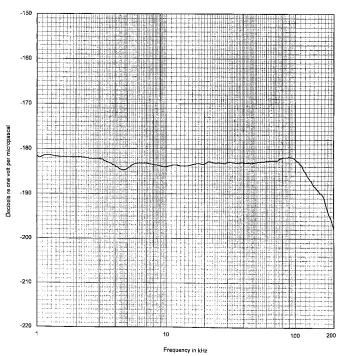


Fig. 8. Measured FFVS of a 25.4 cm by 25.4 cm by 6.35 mm Sono Panel $^{\rm TM}$ in an open water Lake Facility.

responses seen for the smaller sample of Fig. 5 are noted, with the exception of the upper frequency modal behavior.

The success of the low modal contamination in the transmitting responses, coupled with the clean piston mode directivity responses has resulted in increased interest for using these panels in underwater transmitting applications. To study the acoustic output linearity as a function of drive voltage, the 25.4-cm by 25.4-cm by 6.35-mm thick SonoPanelTM sample was driven at 100 $V_{\rm rms}$, 200 $V_{\rm rms}$, 500 $V_{\rm rms}$, 700 $V_{\rm rms}$ and 900 $V_{\rm rms}$. The results of this study are presented in Fig. 10 in which the sound pressure level is shown to increase linearly as a function of the drive level. The study was concluded at 900 $V_{\rm rms}$ because of amplifier limitations.

V. Acoustic Performance Under Hydrostatic Pressure

Underwater acoustical performance evaluations of the 1-3 piezocomposite SonoPanel $^{\rm TM}$ material configuration were investigated as functions of hydrostatic pressure and temperature. These measurements were done at the USRD high pressure Anechoic Tank Facility (ATF). The frequency coverage of the measurements was from 10 to



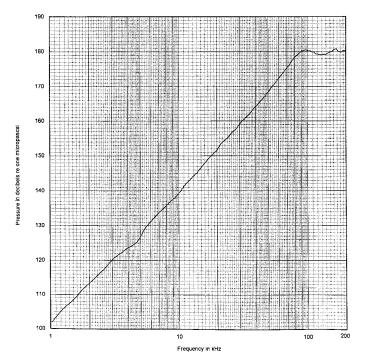


Fig. 9. Measured TVR of a 25.4 cm by 25.4 cm by 6.35 mm Sono Panel $^{\rm TM}$ in an open water Lake Facility.

 $100~\rm kHz$ at the discrete temperatures of 4 and $22^{\circ}\rm C$ under hydrostatic pressure conditions ranging from 138 kPa to almost 7 MPa. The sample used for these measurements was the same 10.16-cm by 10.16-cm by 6.35-mm sample initially evaluated in the Lake Gem Mary Facility.

The effect of the hydrostatic pressure cycling and low temperature exposure on the TVR is demonstrated in Fig. 11. When measured at 4°C, the TVR showed a few decibel variations due to the change in pressure when stepping up from 3.5 to 6.9 MPa, then reduced to 3.5 MPa before returning the system to the ambient pressure. This suggests that the extreme high pressure of 6.9 MPa had a slight effect in degrading the transmitting response, but the response quickly adapted to the new hydrostatic pressure exposure. No changes were noted in the responses as a function of hydrostatic pressure at 22°C.

The low temperature and hydrostatic pressure effect on the overall acoustical property of the SonoPanelTM sample is perhaps more clearly seen when examining the FFVS response of Fig. 12. Nominally a constant FFVS at -185 to -186 dB was observed over the frequency band of the measurement. When pressure cycling was carried out at 22°C, with the pressure varied between ambient pressure to a maximum of 6.9 MPa, the effect on the acoustic performance was found to be less than 1 dB degradation. After the release of this pressure, the material appeared to

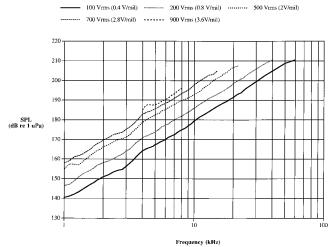


Fig. 10. Measured SPL of a 25.4 cm by 25.4 cm by 6.35 mm SonoPanelTM in an open water Lake Facility for drive voltages of 100 $V_{\rm rms}$, 200 $V_{\rm rms}$, 500 $V_{\rm rms}$, 700 $V_{\rm rms}$, and 900 $V_{\rm rms}$.

recover fully with no change from the original FFVS characteristics. When tested at 4° C, the sensitivity decreased by as much as 4 dB, which suggests that the host matrix polymer properties need to be stabilized before full performance may be realized. The sample returned to its initial performance upon release of the pressure.

VI. Underwater Explosive Shock Tests

In many underwater applications, there is an interest in assuring that an underwater system can withstand an underwater explosive shock and continue to be operationally effective after this exposure. In order to quantify the criteria of the shock, a set of criteria has been established [8]. Fulfillment of this specification requires the structure being examined to remain functionally operational after a series of explosions at four ranges: shot 1 is directed to the edge of the test structure at a distance between the explosion and the test structure of 12 meters, shots 2 through 4 are oriented for broadside interaction at distances of 9, 7.6, and 6 meters, respectively. The explosive charge weight and composition is 60 lb of HBX-1 at a test depth of 3 meters.

Fig. 13 (top) shows a pressure signature from a 9 meter range open-water test shot at the former Hunters Point Navy test facility in California [8]. The peak pressure here is equivalent to approximately 14 MPa with the recoil from the floating platform occurring 600 msec after the peak pressure. The profile for the 6 meter broadside explosion is similarly shaped with a peak pressure of 18 MPa.

The USRD developed a facility to expedite this process for small transducer samples. This facility is the Conical Shock Tube (CST) Facility, which duplicates the conditions of the open-water shock tests, but with a size limitation that the test object fit inside a 10-inch diameter cylinder [9]. The concept of the CST is that, when an explosive charge such as 27.2 kg of HBX-1 is detonated in the

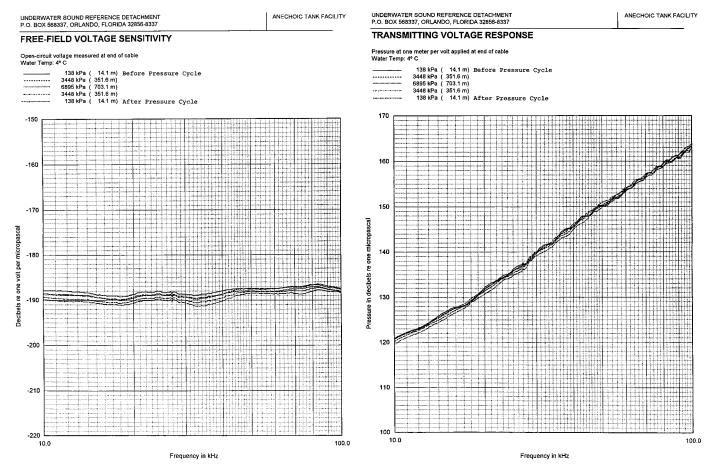


Fig. 11. Measured TVR of a 10.16 cm by 10.16 cm by 6.35 mm SonoPanel $^{\rm TM}$ as a function of hydrostatic pressure and at 4°C in an anechoic tank facility.

Fig. 12. Measured FFVS of a 10.16 cm by 10.16 cm by 6.35 mm SonoPanelTM as a function of hydrostatic pressure and at 4° C in an anechoic tank facility.

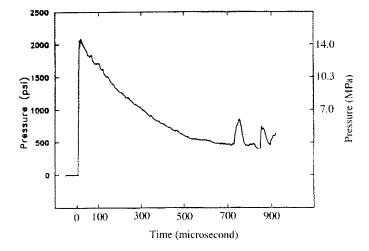
open water, a spherical shock pressure wave is propagated out from the explosion in all directions. The conical bore of the CST represents a small angular sector of the sphere such that an explosive shock pressure wave of the same intensity can be produced by a small angular sector of the original charge at the vertex of the cone. This also means that, by using a charge weight of a #8 blasting cap and less than 1 gram of flexible booster explosive, a shock wave can be produced that is equivalent in peak pressure and time profile to that of the 6 meter range broadside impact. To try and maintain the exact profile of the open-water shock tests, a sliding piston was installed in the CST behind the location of the test device. This piston behaves in a similar recoil fashion as that of the actual floating platform.

To investigate whether functional performance changes occur in the 1-3 piezocomposite plates after exposure to underwater shock in the CST, acoustic measurements were conducted at USRD in the Lake Gem Mary Facility for the 1 k to 200 kHz frequency range and in the High Frequency Calibration Facility for the 200 k to 400 kHz frequency range. Acoustic measurements included the TVR, FFVS, and directivity responses.

After initial acoustic measurements, the SonoPanel $^{\rm TM}$ sample was exposed to shock waves representative of a broadside 6 meter range explosive shock in the CST Facil-

ity. Fig. 13 (bottom) shows the shock pressure signature for this explosion. When compared with the shock wave pressure profile of Fig. 13 (top), the CST shock wave peak appears more rounded. Also, higher frequency overtones produced noticeably more scatter in the pressure response as a function of time. Both of these characteristics are traits of the steel tube. Although the appearance on the pressure wave profile is different, this high frequency energy does not contribute much to the total energy in the spectrum [9]. A conversion of the units in Fig. 13 shows good agreement between the two pressure profiles in terms of time scale occurrences. The pressure levels for Fig. 13 (top) are less because its profile is for a 9 meter range and that of Fig. 13 (bottom) represents a 6 meter range.

Fig. 14 is a presentation of the TVR [Fig. 14 (a)] and FFVS [Fig. 14 (b)] for a SonoPanelTM 1-3 piezocomposite sample before and after the underwater explosive shock exposure. In fact, because there was no degradation after the first explosive shock exposure, this transducer was later exposed a second time and acoustically measured a third time. Again, no degradation was observed in the transmitting and receiving responses. Note that the slight differences seen above 180 kHz are due to mounting errors during the acoustic measurements and are not a resulting indication of the shock exposure.



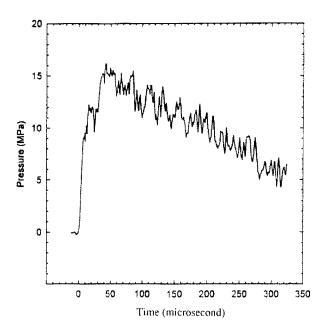


Fig. 13. Top. Open-water shock pressure wave profile from a 9 meter range broadside test shot at the former Hunters Point Shock Facility. Bottom. Conical shock tube pressure wave profile for an equivalent broadside 6 meter range test shot. This profile was recorded during the exposure of the SonoPanel $^{\rm TM}$ sample.

VII. SUMMARY

A specific 1-3 piezocomposite configuration known as the SonoPanelTM has been fabricated by using a cost-effective injection molding technique. The in-air and inwater measured performances show not only modal behaviors related to piezoceramic rod spacings and matrix polymer selections, but they also show a relatively well behaved acoustic response. The measured underwater directivity responses suggest a pure piston mode response. The present panel configuration appeared to be stable with hydrostatic pressure up to 6.9 MPa and is resistant to explosive shock as determined from tests in a conical shock tube. The underwater acoustical performance suffers its most severe test when the composite panel is exposed to

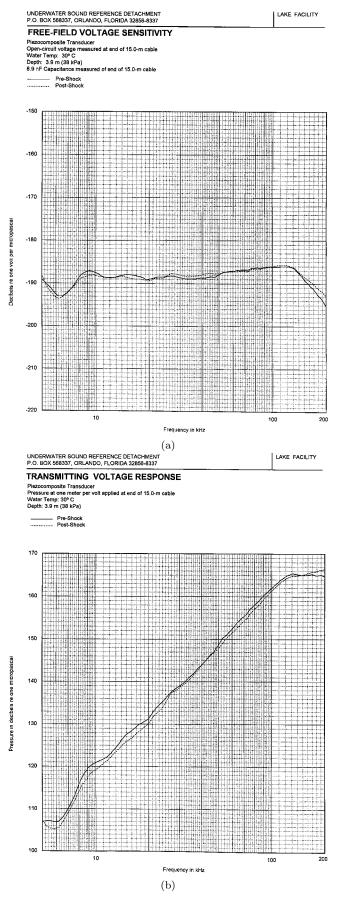


Fig. 14. Measured TVR (a) and FFVS (b) for the SonoPanel $^{\rm TM}$ 1-3 piezocomposite structure before and after the underwater explosive shock exposures.

the combination of high hydrostatic pressure of 6.9 MPa and a low temperature of 4°C. In summary, the 1-3 piezo-composite SonoPanelTM configuration has high sensitivity, flat broadband response, and linearity with respect to drive voltage. This material configuration appears to be a promising candidate for underwater transducer applications when large area coverage is desired.

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Dr. Howarth holds two patents (with another four pending), presented and/or published more than 70 papers, and was the charter recipient of the ASA Structural Acoustics TC's First Prize in the Student Paper Competition in May 1991. He is a member of Tau Beta Pi.



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